The Changes in Gait Patterns after Body Weight Supported Treadmill Training in a Patient with an Incomplete Spinal Cord Injury

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Abstract

Body weight supported treadmill training (BWSTT) is a therapy used to help individuals with a spinal cord injury (SCI) regain the ability to walk. During BWSTT, patients are supported by a harness over a treadmill while therapists provide manual assistance to move the patient's legs through a normal gait pattern. In order for BWSTT to be effective, it is believed that the therapy must replicate the forces and motions of normal gait. While this therapy is successful, not all patients respond in the same way and gait abnormalities exist following therapy.

We collected kinematic and kinetic gait data from one individual with a SCI who has completed BWSTT. We tested the subject in the training environment at three speeds (self-selected (SS), 50% SS, and 150% SS) and at five levels of body weight support (BWS) (0%, 10%, 30%, 50%, and 70%). We analyzed lower extremity joint kinematics and kinetics, ground reaction forces, and the ankle-foot roll-over shape and compared with health subjects. The SCI subject lacked plantarflexion throughout most of the gait cycle, and his kinematics differed from healthy subjects during initial ground contact. The joint kinetics were variable between gait cycles, especially during midstance. The patient did not have an ankle-foot roll-over shape for the majority of the conditions. Since it is unknown how a person walks after regaining the ability to walk with BWSTT, this research is a step towards understanding and improving the outcomes from BWSTT.

Acknowledgments

First of all I would like to thank my research advisor Dr. Robert Siston. Without your encouragement I most likely would have not considered an undergraduate research project. You were always willing to answer my endless questions when I stopped in your office multiple times a day. You have been extremely helpful and supportive throughout this whole process, while always pushing me to do more. I'm looking forward to working with you for graduate school.

Thank you to Dr. Michele Basso and Lise Worthen-Chaudhari for your feedback and ideas. Your clinical input has been invaluable to my understanding and appreciation for this research project. I would like to thank Dr. Jim Schmiedeler and Dr. Ajit Chaudhari for your help and opinions with this project. I would like to thank Dr. Alison Sheets for taking the time to be on my defense committee and provide me feedback on this research. A very big thanks to Becky Lathrop and Brooke Morin for helping me get adjusted to this project and for all their support and guidance. Becky, thank you for helping me understand the concepts behind this research and helping me figure out Vicon, OpenSim, and all the data I had to process. Brooke, thank you for also helping me understand Vicon and for processing the roll-over shape on such short notice. I would also like to thank the rest of the NMBL lab – Julie, Erin H, Erin P, and Becca, for their encouragement and feedback on my research.

Finally I would like to thank all my family and friends for all their support. Thanks to my mom and dad for always encouraging me and believing in me. Thanks to my dad and brother for teaching me how to build a deck, which I never thought would be possible. A big thanks to my sisters Katie and Maggie for always being there for me when I needed to vent and for making me laugh when I needed it - I don't think I would be sane without you two.

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1. Introduction

There are more than 250,000 people in the United States living with a spinal cord injury (SCI), and over 12,000 people are injured each year (NSCISC, 2010). People affected by a SCI will face many difficulties in their lives, and they lose a great deal of independence after injury. The health care costs for these injuries are very high, and it is hard for many people with an SCI to return to work, causing an economic hardship (NSCISC, 2010).

Regions of the spinal cord control separate areas of the body, as shown in Figure 1.1. A SCI will affect the control of the region at the level of injury; and all regions inferior to the injury. The extent of control lost depends on the severity of the injury. People who have a complete SCI will lose all function below the level of the injury, while people who have an incomplete injury will still have some motor or sensory function below injury level (Trieschmann, 1988). Since the lumbar region, which controls the legs, is inferior to most regions of the spinal cord, locomotion is usually affected by a SCI.

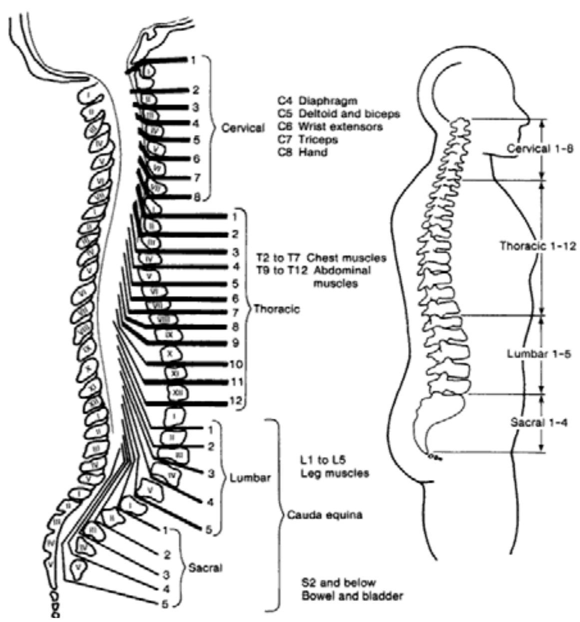

Figure 1.1 Functions in the body controlled by different regions of the spinal column (Trieschmann, 1988)

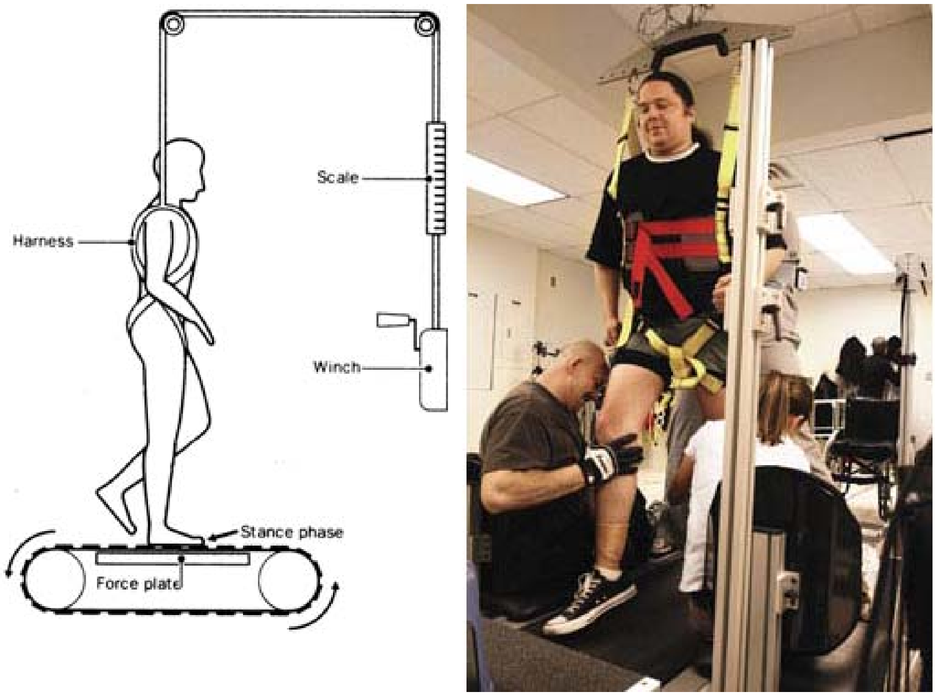

Figure 1.2: a) Schematic of BWSTT (Van de Crommert et al., 1998) b) A patient during BWSTT at Ohio State University (photo courtesy of medicalnewstoday.com)

A form of therapy known as body weight supported treadmill training (BWSTT) has been effective in helping individuals with an incomplete SCI regain their ability to walk (Barbeau et al., 1987). In BWSTT, patients are positioned over a treadmill by a harness used to support a portion of their body weight (Figure 1.2). They are then assisted by therapists who help move the patients' legs through a normal gait pattern. As the patients' ability to walk increases, therapists provide less assistance and the amount of body weight support is decreased.

BWSTT is based on the theory that locomotion is controlled by a network of neurons located in the spinal cord, known as the central pattern generator (CPG). The CPG is believed to produce rhythmic, patterned outputs without continuous input from the brain. This rhythmic pattern is fine-tuned by load and position feedback in the lower extremities, creating the closed-loop system shown in Figure 1.3 (Van de Crommert et al., 1998). Extensive evidence exists for a CPG in cats and other vertebrates, while evidence for a CPG in humans is limited (Duysens and Van de Crommert, 1998).

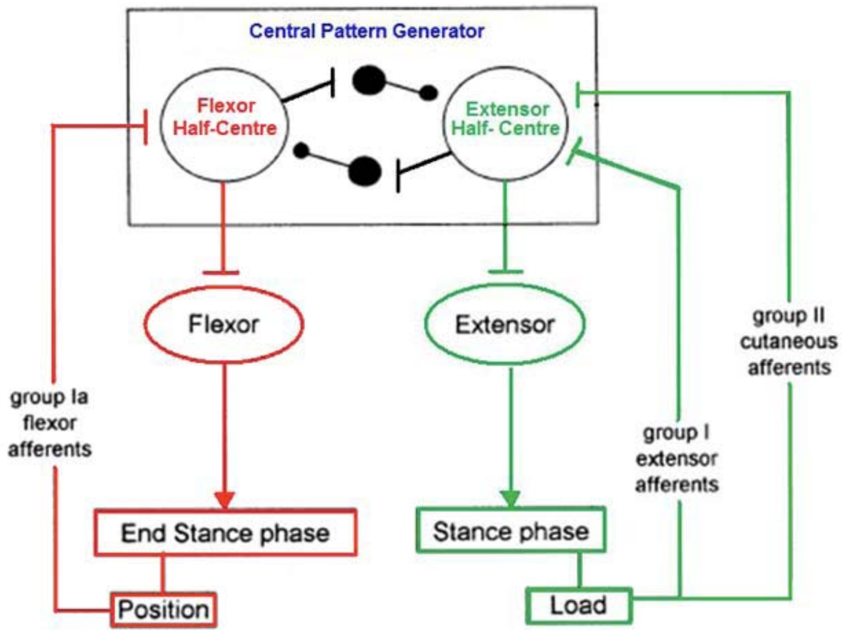

Figure 1.3: Model of the CPG, which uses afferent feedback from load and position sensors to control flexion and extension during gait (Adapted from Van de Crommert et al.,1998)

It is believed that this therapy must replicate both the forces and motions that are seen during normal gait, in order to provide proper feedback to the CPG. Two parameters that can affect these forces and motions during training are treadmill speed and percentage of BWS (Hidler, 2005). Currently these values are set based on what the therapists believe “looks right”, which leads to high variability in training parameters.

Although results of BWSTT are generally positive, one study showed that 76% of patients with an incomplete SCI could walk independently after therapy (Wernig, 1995), some issues still exist. Anecdotal evidence from therapists show that there are some functional deficits following training, including lack of trunk control and toe-drag. The results also vary from patient to patient, and not all individuals are able to walk independently after therapy (Wernig, 1995). Due to these inconsistent outcomes, there is a need for additional research on BWSTT so that all patients can achieve positive outcomes.

Research in our lab has established a baseline on the effects of varying BWS and treadmill speed on healthy individuals' gait patterns. This research found that changing speed and BWS has a significant effect on both lower extremity joint kinematics and kinetics (Lathrop, 2009). This work also shows that as therapist choose a treadmill speed and BWS combination that produces correct kinematics, the patients might not always produce joint moments that correspond to normal gait. Previous research has shown the ankle-foot roll-over shape to be invariant for multiple walking conditions including varied speed, increased weight, and walking at an incline (Hansen et al., 2004). Research in our lab found this shape was not invariant when BWS and treadmill speed were changed (Morin, 2009).

1.1 Focus of Thesis

This undergraduate research project is a pilot study that explores the gait patterns of 1 SCI patient after he regained the ability to walk following BWSTT. We will analyze joint kinematics, joint kinetics, ankle-foot roll-over shape, and the path of the foot during gait and compare this data to the same data in healthy subjects.

1.2 Significance of Research

Little is known about the gait patterns of a person after rehabilitation from a SCI. This pilot study will provide information on how a person walks following BWSTT and will assist in determining areas of focus for larger studies. The protocols for BWSTT cannot be improved until it is known what areas need improvement.

1.3 Overview of Thesis

This thesis contains five chapters. Chapter 2 describes the methodology used for data collection and analysis. The results are presented and discussed in Chapters 3 and 4, respectively. Chapter 5 contains a summary and conclusion of this research, and suggestions for future work.

2. Experimental Methods

We collected kinetic and kinematic data from 1 male subject who had completed BWSTT following a SCI. Informed consent was obtained prior to the subject's participation in this study.

2.1 Equipment and Data Collection

We collected data at the NeuroRecovery Network (NRN) located in the Dodd Rehabilitation Hospital at the Ohio State Medical Center. We used one of two functioning BWSTT stations to collect our data (Figure 2.1).

A closed-loop pneumatic force control system (Vigor Equipment, Stevensville, MI; Tescom, Elk River, MN) was used for the constant BWS on the subject. The subject walked on an instrumented split belt treadmill (Bertec Corp., Columbus, OH) with embedded force plates that recorded ground reaction forces (GRFs) and center of pressure (COP) data. Seven Vicon cameras were placed around the room to record kinematic data as the subject walked on the treadmill (Vicon Mxcameras, Vicon, Inc.) (Figure 2.2).

Figure 2.1: BWSTT station used for data collection

Figure 2.2: Vicon camera used for motion capture

The subject was fitted into a two-part medical harness used by patients in the NRN. The upper and lower portions of the harness were connected by four straps, supporting both the torso and pelvis (Figure 2.3). Once the subject was wearing the harness, the subject's self-selected (SS) walking speed was determined by a 10-meter overground walking trial. The subject's weight and height were recorded, then the upper part of the harness was then connected to the BWS system.

Figure 2.3: Two part medical harness

Optical, marker-based motion capture data was collected using a Point Cluster Technique (Andriacchi et al., 1998). The Point Cluster Technique uses an overabundance of markers placed on the thigh and shank in order to reduce error from soft tissue movement in the lower extremities. Forty-one markers were placed on anatomical landmarks, and fifteen markers were used for the marker clusters. These cluster markers (Figure 2.4) are then used to define cluster-coordinate systems for the thigh and shank that are more closely related to the rigid motion of the lower extremities (Andriacchi et al., 1998).

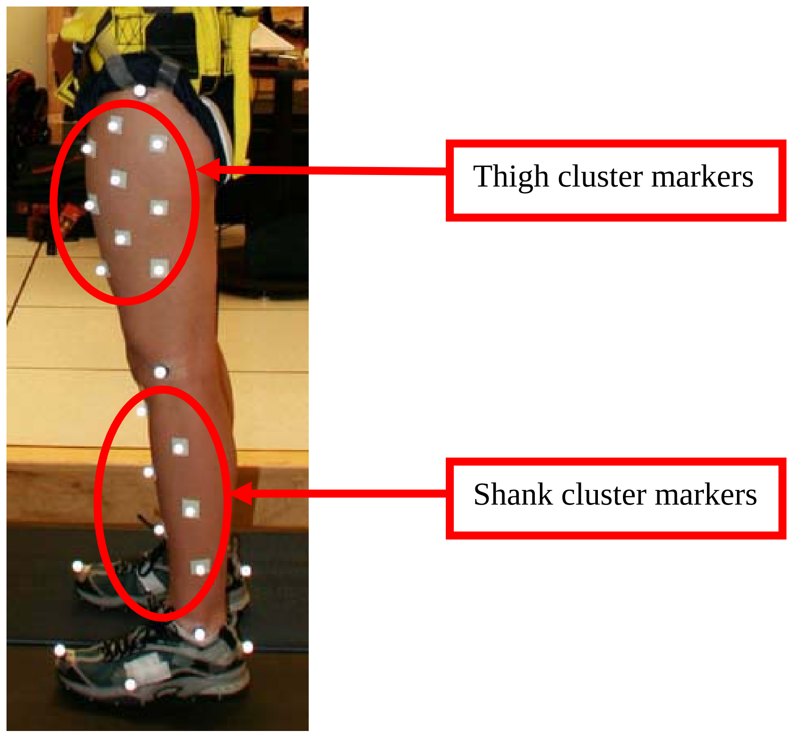

Figure 2.4: Reflective markers used for cluster-coordinate systems

Once the subject was on the treadmill with markers attached, he participated in a practice session to become familiar with the treadmill and set up. During the practice session, he walked on the treadmill with no BWS at his SS speed and then at the extremes of BWS and treadmill speed.

After the practice session, GRFs and motion capture data were collected at 200 Hz as the subject performed 11, 30 second trials, with a rest period between trials. The conditions were 30%, 50%, and 70% BWS each at 50%, 100%, and 150% SS walking speed, 10% BWS at SS walking speed, and 0% BWS at 50% SS walking speed. These values were chosen because they include ranges which patients typically train at during therapy (Dietz et al., 2002).

2.2 Data Processing

We used ViconNexus software to determine the three dimensional position of each relective marker. The markers were then labeled according to their anatomical position on the subject, which allowed us to view a digital version of the subject's motion. Matlab code developed by Professor Ajit Chaudhari of the Ohio State University Sports Biomechanics Research Lab was used to create the shank and thigh coordinate systems from the cluster markers (Figure 2.5). We chose ten consecutive gait cycles for each condition, starting and ending at left heel-strike.

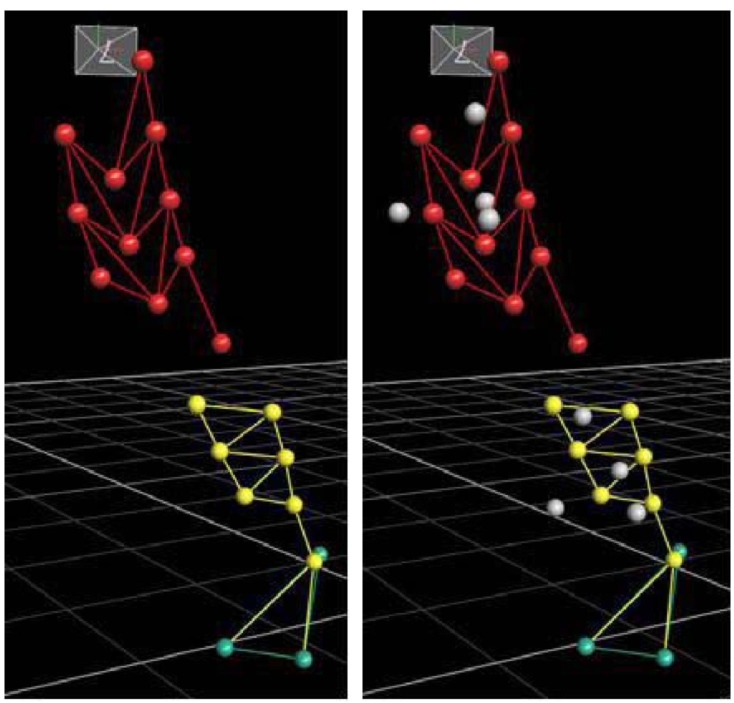

Figure 2.5: a) Cluster markers b) shank and thigh coordinate systems from cluster markers

2.2.1 Kinematics and Kinetics

The motion capture data from ViconNexus and the ground reaction forces for the ten gait cycles were imported into OpenSim. OpenSim (Stanford University, Stanford CA) is an open source software program used for biomechanical modeling (Delp et al., 2007). A subject-specific model was created by scaling a generic musculoskeletal model based on the subject's anatomical measurements. The OpenSim model had rigidly attached markers in the same locations as the markers on the subject during data collection (Figure 2.6).

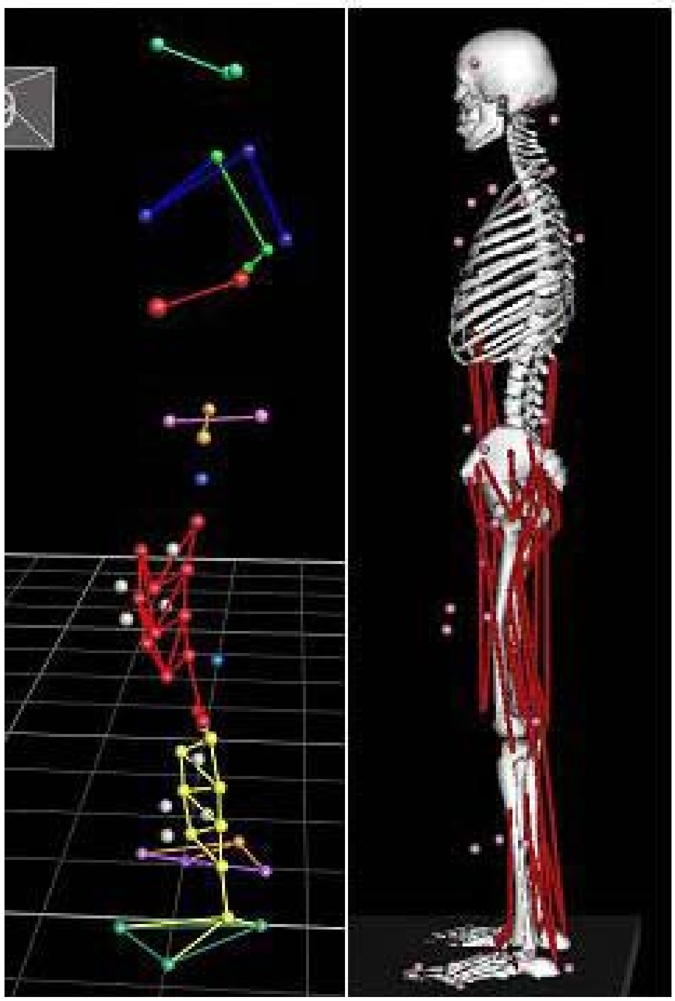

Figure 2.6: a) Experimental marker in ViconNexus b) Markers attached to OpenSim model

The marker trajectories were loaded into OpenSim using the inverse kinematics tool. The inverse kinematics tool uses a weighted least squares fit to minimize the error between the experimental motion capture markers and the virtual markers attached to the model (Delp et al., 2007). We then used this to determine the ankle and knee joint angles throughout each gait cycle.

The inverse dynamics tool in OpenSim used the ground reaction forces and joint kinematics to solve equations of motion that determine the joint moments that produce the movement of the model. The equations used to solve for kinetics at the ankle, knee, and hip joints are given below.

$$F_a = m_f a_f - F_G + m_f g \tag{2.1}$$

$$M_a = -T_G - r_{aCOM,p} x F_a - r_{aCOM,d} x F_G + I_f \alpha_f \tag{2.2}$$

$$F_k = m_s a_s - F_a + m_s g \tag{2.3}$$

$$M_k = -M_a - r_{kCOM,p} x F_k - r_{kCOM,d} x F_a + I_s \alpha_s \tag{2.4}$$

$$F_h = m_t a_t - F_k + m_t g \tag{2.5}$$

$$M_h = -M_k - r_{hCOM,p} x F_h - r_{hCOM,d} x F_k + I_t \alpha_t \tag{2.6}$$

where subscript a is the ankle, subscript f is the foot, subscript G is the ground reaction force, subscript k is the knee, subscript s is the shank, subscript h is the hip, and subscript t is the thigh. The distance from the center of mass to the proximal and distal end of a segment is shown by $r_{aCOM,p}$ and $r_{aCOM,d}$, respectively. The inverse dynamics tool solved these equations for each gait cycle and ankle, knee, and hip joint moments were calculated.

Along with joint angles, we calculated the angle of the foot in relation to the ground. This angle in the sagittal plane was defined as the angle between a vector pointing from the calcaneus marker to the 2nd metatarsus marker and a unit vector on the ground pointing to the anterior direction of the body, using the dot product.

2.2.2 Ankle-Foot Roll-Over Shape

The ankle-foot roll-over shape is a simple metric that combines both the forces and motion during gait, and is based on the rocker-based inverted pendulum theory of walking. This shape, which occurs from heel contact to opposite heel contact, is found by transforming the center of pressure (COP) in the sagittal plane into a shank-based coordinate system (Figure 2.7).

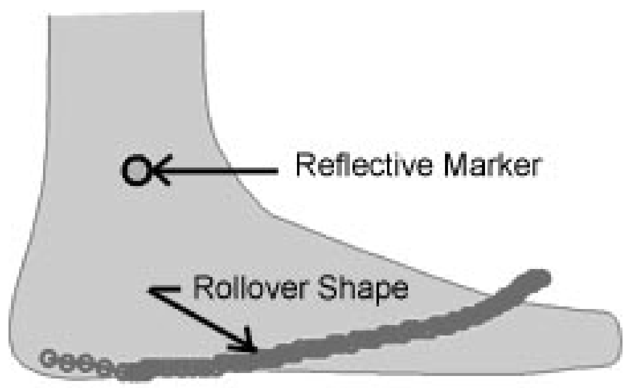

Figure 2.7: Schematic of the ankle-foot roll-over shape

To find this roll-over shape, we used five reflective markers: the lateral malleolus, calcaneus, 2nd metatarsal, and lateral epicondyle on the left side and the 2nd metatarsal on the right side (Figure 2.8). A unit vector in the direction from the lateral malleolus to the lateral epicondyle was defined as the Z-axis of the shank-based coordinate system. The y-axis was defined as the cross product of the z-axis, and a unit vector in the direction from the calcaneus to the 2nd metatarsal. The x-axis was defined by the cross product of the z-axis and the y-axis.

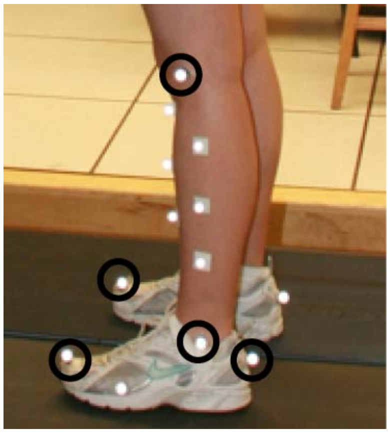

Figure 2.8: Reflective markers used for ankle-foot roll-over shape

After the shank-based coordinate system was defined, the COP from the force plate was transformed into it using Equation 2.7, where (x_T, y_T, z_T) are the transformed coordinates, R is a 3x3 rotation matrix, P is a 3x1 translation vector, and (x_0, y_0, z_0) are the initial coordinates. We then fit a circular arc to the transformed COP data using circle-fitting code from the MathWorks website (Buscher, 2004).

$$\begin{bmatrix} x_T \\ y_T \\ z_T \\ w \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} & & \\ & R & \\ & & \end{bmatrix} & \begin{bmatrix} \\ P \\ \\ \end{bmatrix} \\ \begin{matrix} 0 & 0 & 0 \end{matrix} & 1 \end{bmatrix}^{-1} \begin{bmatrix} x_0 \\ y_0 \\ z_0 \\ 1 \end{bmatrix} \tag{2.7}$$

The roll-over shape was characterized by the radius of the arc fit to the transformed COP, and anterior shift of the center of the arc. The anterior shift was measured from the lateral malleolus, where a positive displacement is in the direction of the 2nd metatarsus.

2.2.3 Foot path

Another measure used to describe a person's gait is the control of the foot. Research has shown that the path of the foot has very small variability in healthy volunteers, even with BWS up to 95% (Ivanenko et al., 2002). We determined the foot path as the path of the markers on both the 2nd metatarsal and the calcaneus for all ten gait cycles.

2.3 Data Analysis

The same data was previously processed in our lab for eight non-impaired individuals. The non-impaired individuals were tested with the same methods at the same training conditions, except the non-impaired individuals were tested at 0% BWS, 100% SS speed, as opposed to 10% BWS, 100% SS speed that was used for the patient. No statistical analyses were run since this was a case study of 1 person, but the data from non-impaired subjects are presented for comparison.

3. Results

3.1 Kinematic and Kinetic Results

The SCI patient did not have the same amount of plantarflexion as healthy subjects during toe-off, and, at most conditions is in dorsiflexion while pushing off, as shown in Figure 3.1. The SCI patient is also making initial contact with the ground in plantarflexion at high levels of BWS. At faster speeds, the SCI patient does not make initial contact in plantarflexion, but in dorsiflexion as is typically seen in healthy subjects. For the knee angle (Figure 3.2), the SCI patient is in deeper knee flexion during initial contact when compared to healthy subjects. For 50% and 70% BWS, the SCI patient also has more knee flexion during toe-off. The foot angle, shown in Figure 3.3, varies at initial contact with different levels of speed and BWS. At most conditions the foot angle is negative at initial contact, representing the toes further from the ground. At initial contact for 70% BWS, 50% SS speed, the foot angle is positive, representing the toes pointed towards the ground. At slower speeds and at higher BWS, the foot angle is close to zero.

The anterior-posterior (AP) GRF (Figure 3.4) for the SCI patient is smaller in magnitude than for healthy subjects. The healthy subjects exhibit consistent periods of breaking and propulsion in AP GRFs. The SCI patient does not have these periods of breaking and propulsion, or they are out of phase from what is seen in healthy subjects. A typical vertical GRF has 2 peaks, as shown in plots of healthy subjects (Figure 3.5). For the patient at slower speeds, the vertical GRG has only 1 peak, and at the self-selected speed the vertical GRF has 3 peaks. At the faster speed, the vertical GRF has 2 peaks, and is most similar to the healthy subjects.

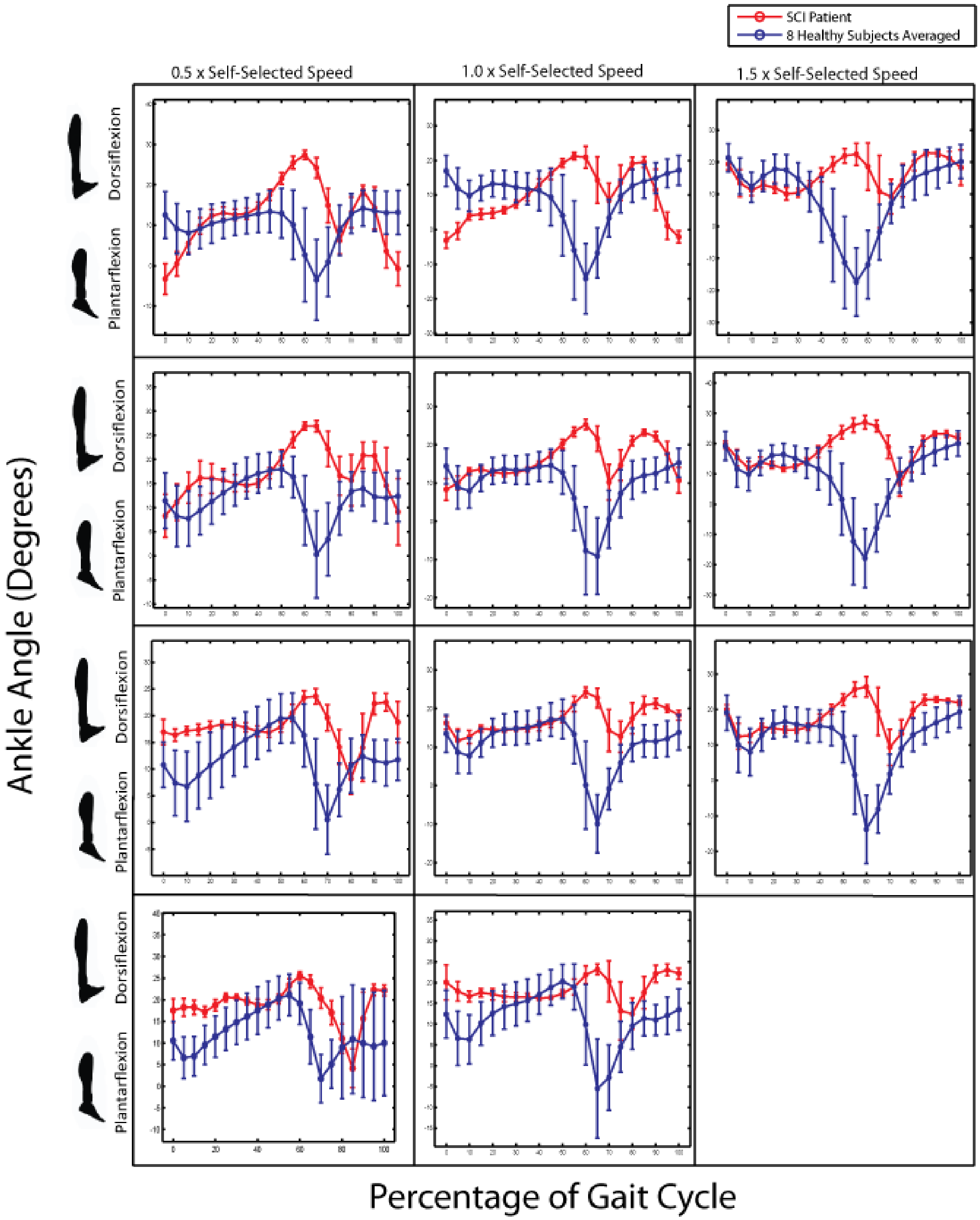

Figure 3.1: Ankle angle averaged for five gait cycles for 3 treadmill speeds and 4 levels of BWS

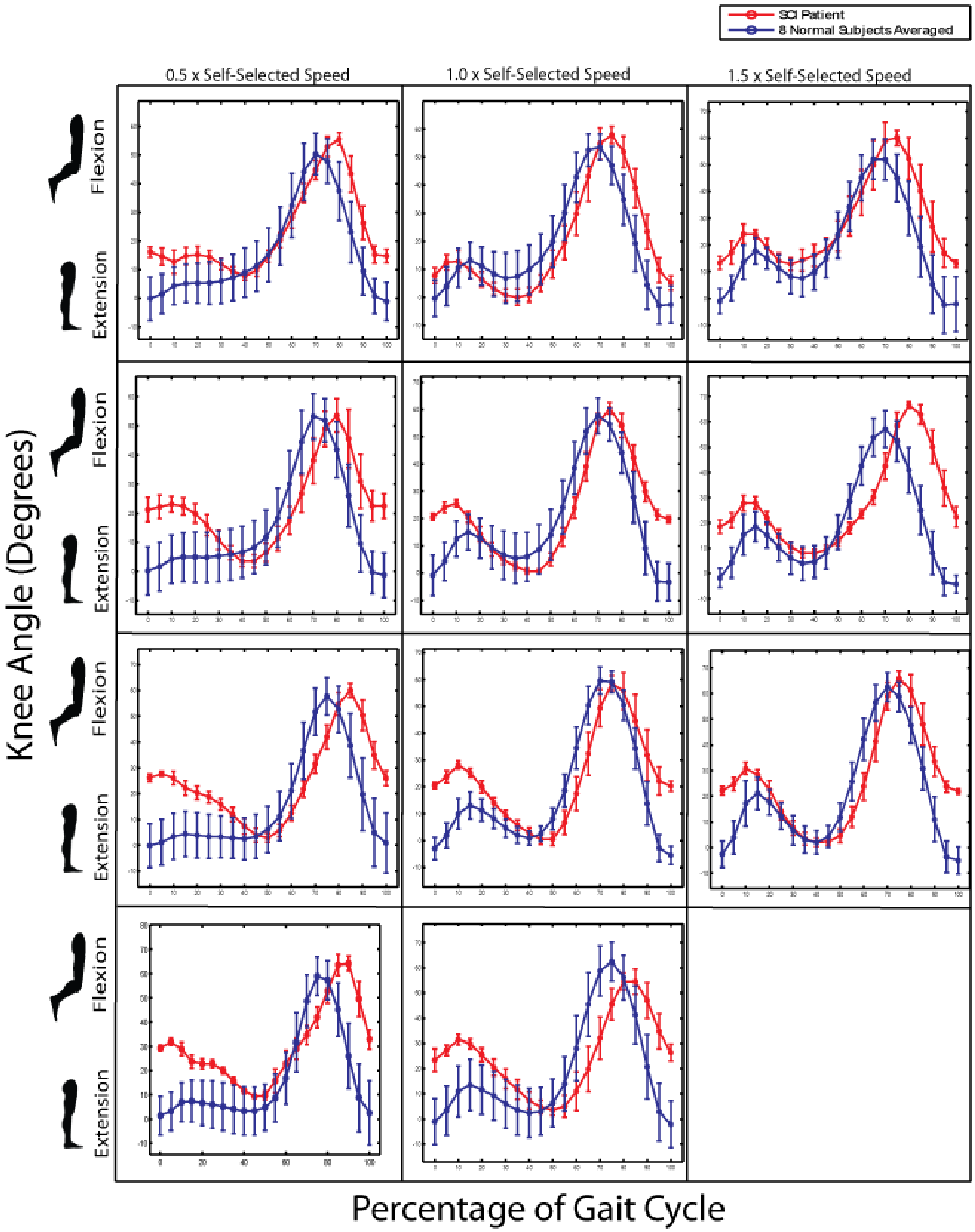

Figure 3.2: Knee angle averaged for five gait cycles for 3 treadmill speeds and 4 levels of BWS

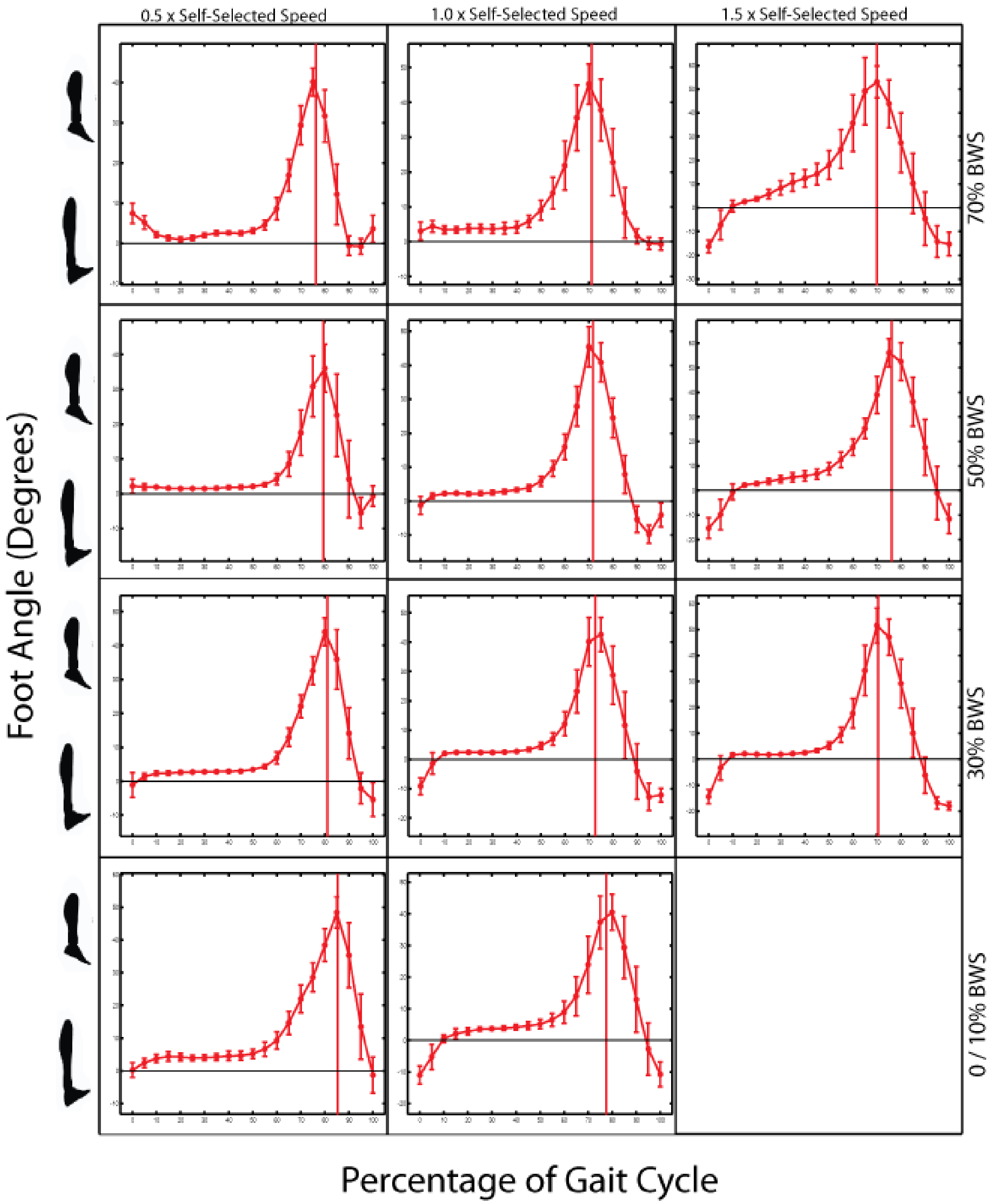

Figure 3.3: Foot angle averaged for five gait cycles for 3 treadmill speeds and 4 levels of BWS. The red vertical line indicates toe-off and the black horizontal line represents zero degrees.

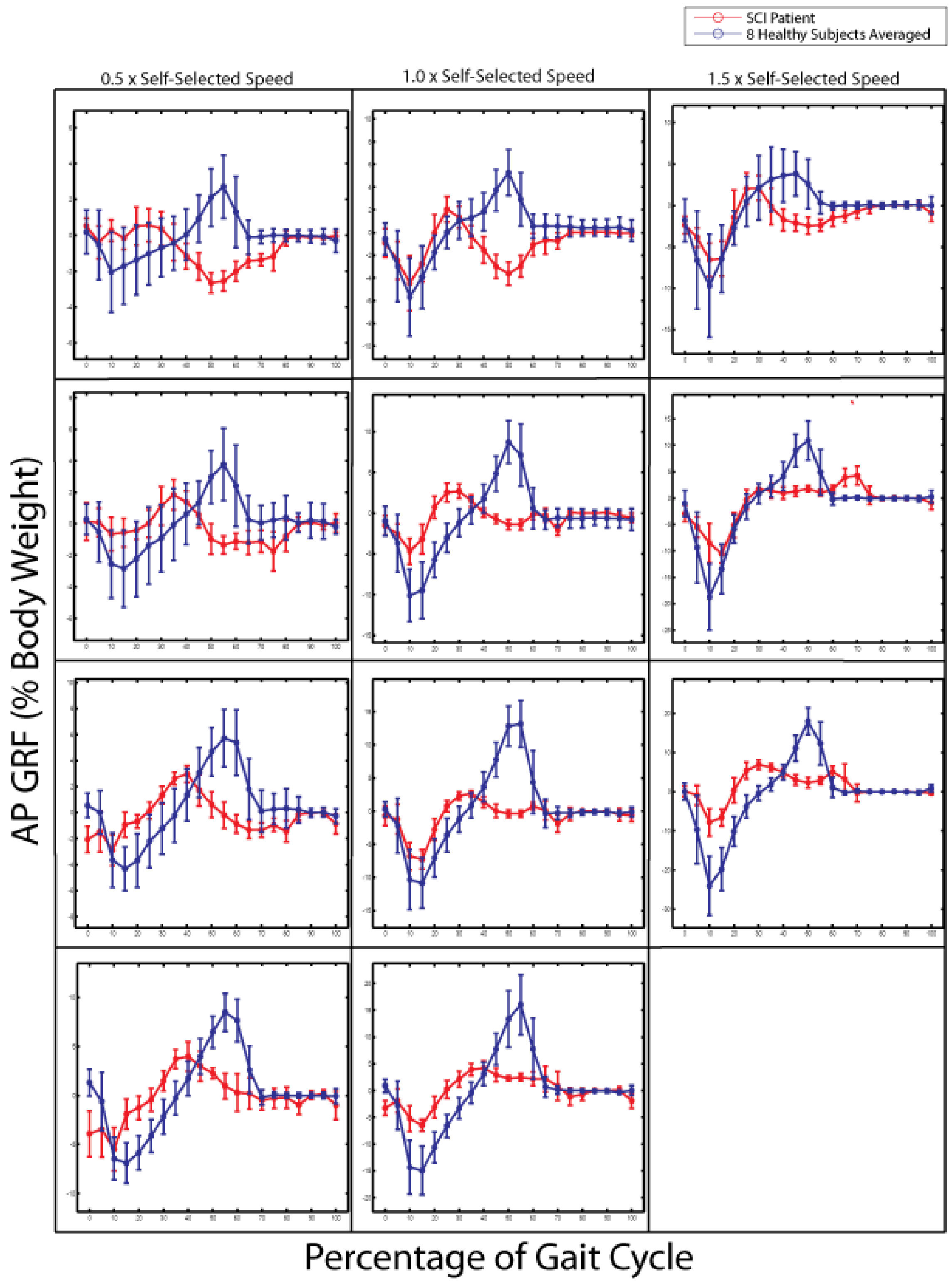

Figure 3.4: AP Ground Reaction Force averaged for five gait cycles for 3 treadmill speeds and 4 levels of BWS

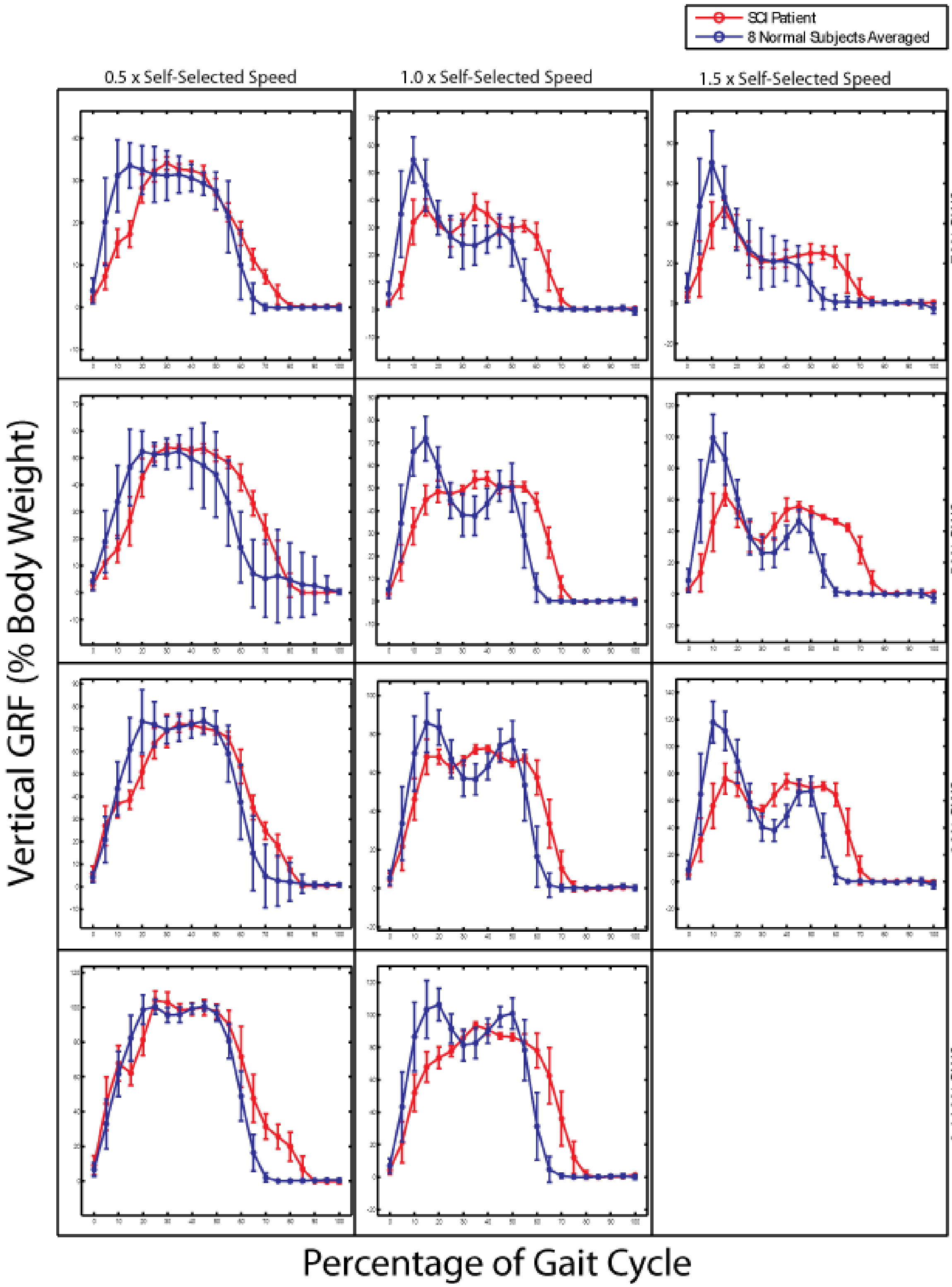

Figure 3.5: Vertical Ground Reaction Forces averaged for five gait cycles for 3 treadmill speeds and 4 levels of BWS

The average joint moments for 5 gait cycles for the ankle, knee, and hip are shown in Figure 3.6, Figure 3.7, and Figure 3.8 for both the SCI patient and 8 healthy subjects. While some small differences between the two groups do exist, the average joint moments for the patient are similar to the average joint moments in healthy subjects.

While the shape of the average joint moments for the SCI patient and healthy subjects are similar, the variability for the SCI patient is high, especially at faster speeds and higher BWS. Figure 3.9 shows the knee moment for 5 individual gait cycles for 1 healthy subject and the SCI patient. The knee moment for the healthy subject has the same shape and is very repeatable between gait cycles, while the knee moment for the SCI patient is highly variable between gait cycles.

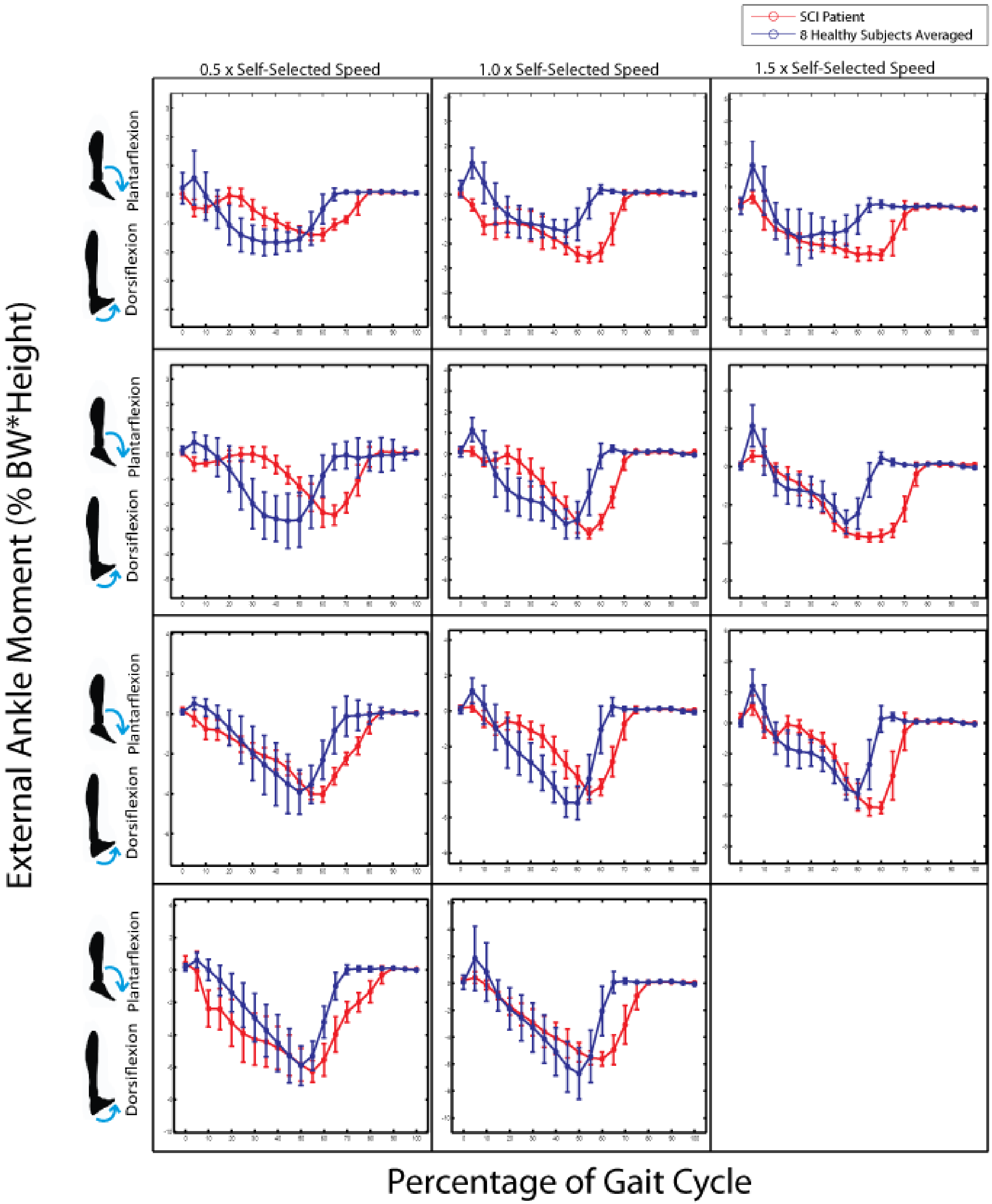

Figure 3.6: Ankle moment averaged for five gait cycles for 3 treadmill speeds and 4 levels of BWS

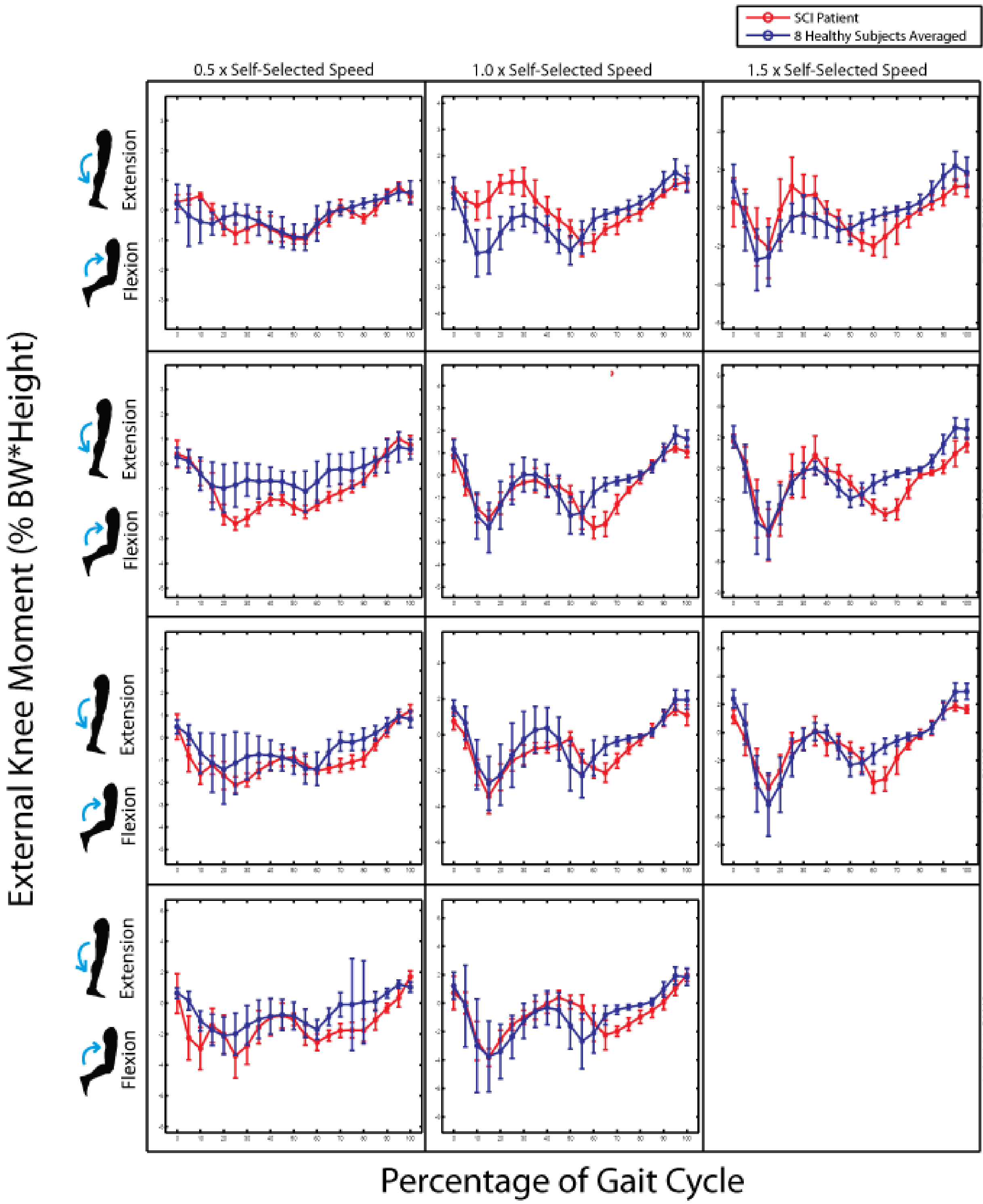

Figure 3.7: Knee moment averaged for five gait cycles for 3 treadmill speeds and 4 levels of BWS

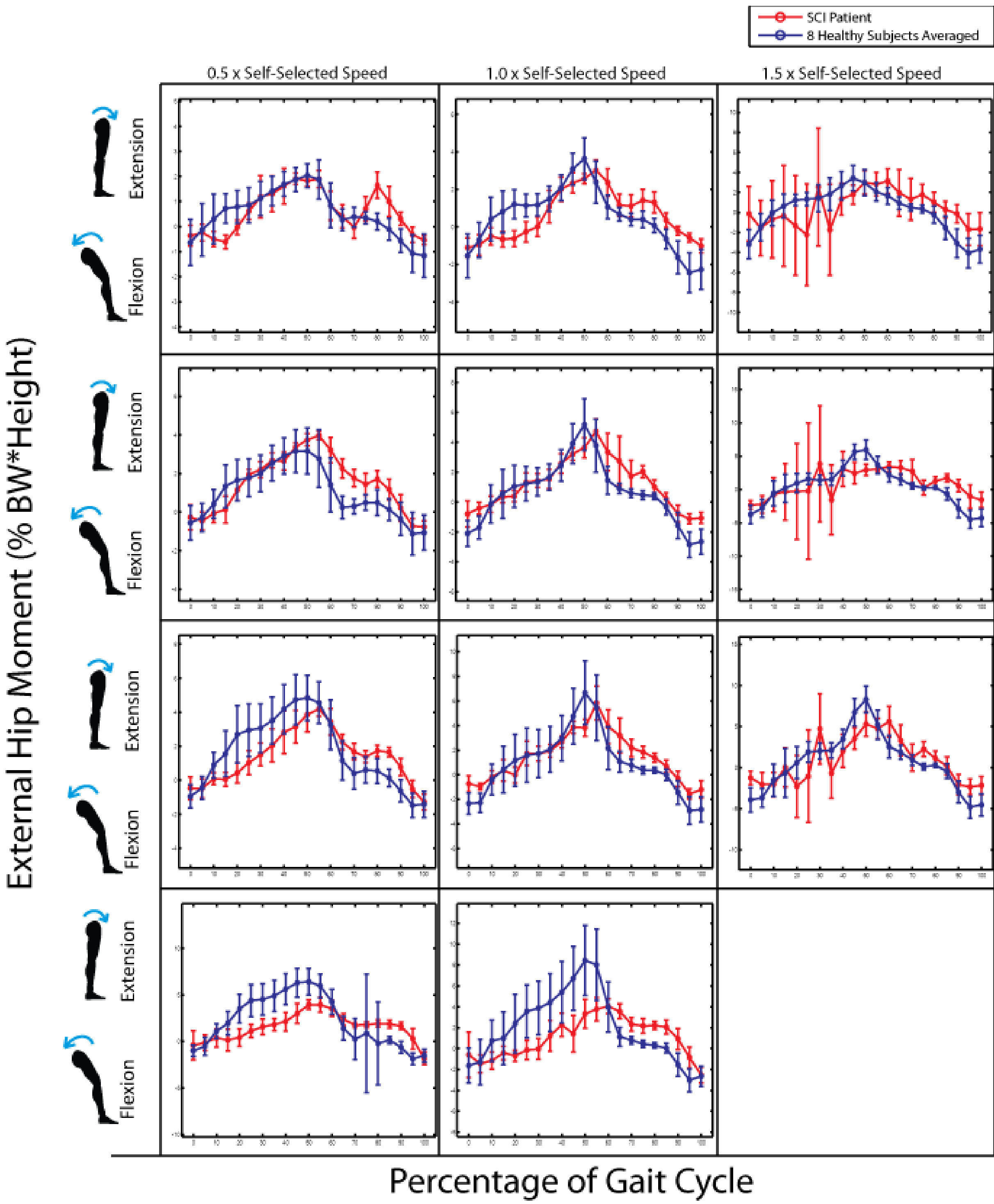

Figure 3.8: Hip moment averaged for five gait cycles for 3 treadmill speeds and 4 levels of BWS

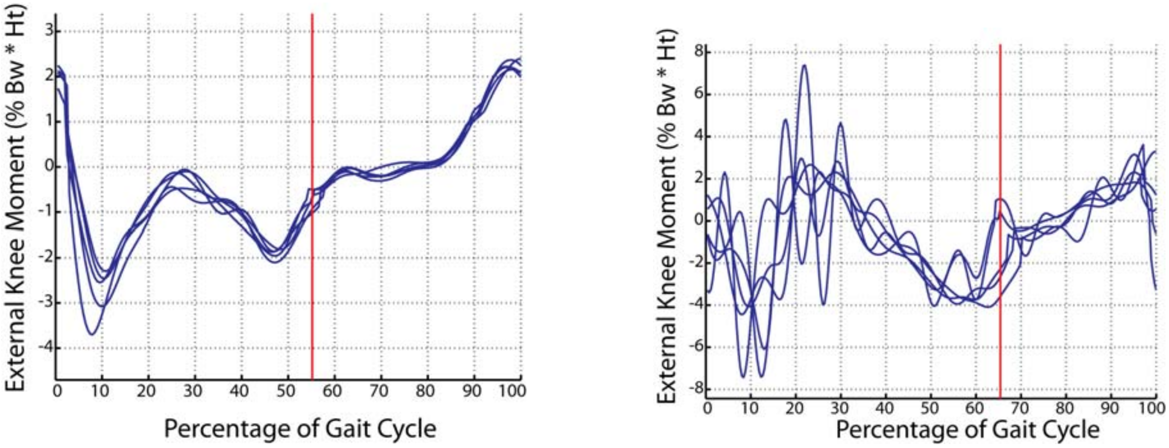

Figure 3.9: Knee moment for five gait cycles for a) a healthy subject and b) SCI patient. The red vertical line indicated toe-off.

The variability in joint moments occurs at all 3 lower extremity joints, as shown in Figure 3.10, Figure 3.11, and Figure 3.12, which plot the joint moments for 5 individual gait cycles for ankle, knee, and hip. This variability increases as treadmill speed and BWS increase, and it also increases the further the joint is away from the ground. While the moments are variable over the entire gait cycle, the highest level of variability is occurring during midstance. Even though the joint moments for the SCI patient are inconsistent between gait cycles, as the 5 cycles are averaged together, the moment closely resembles the joint moment of a healthy subject, as shown in Figure 3.13.

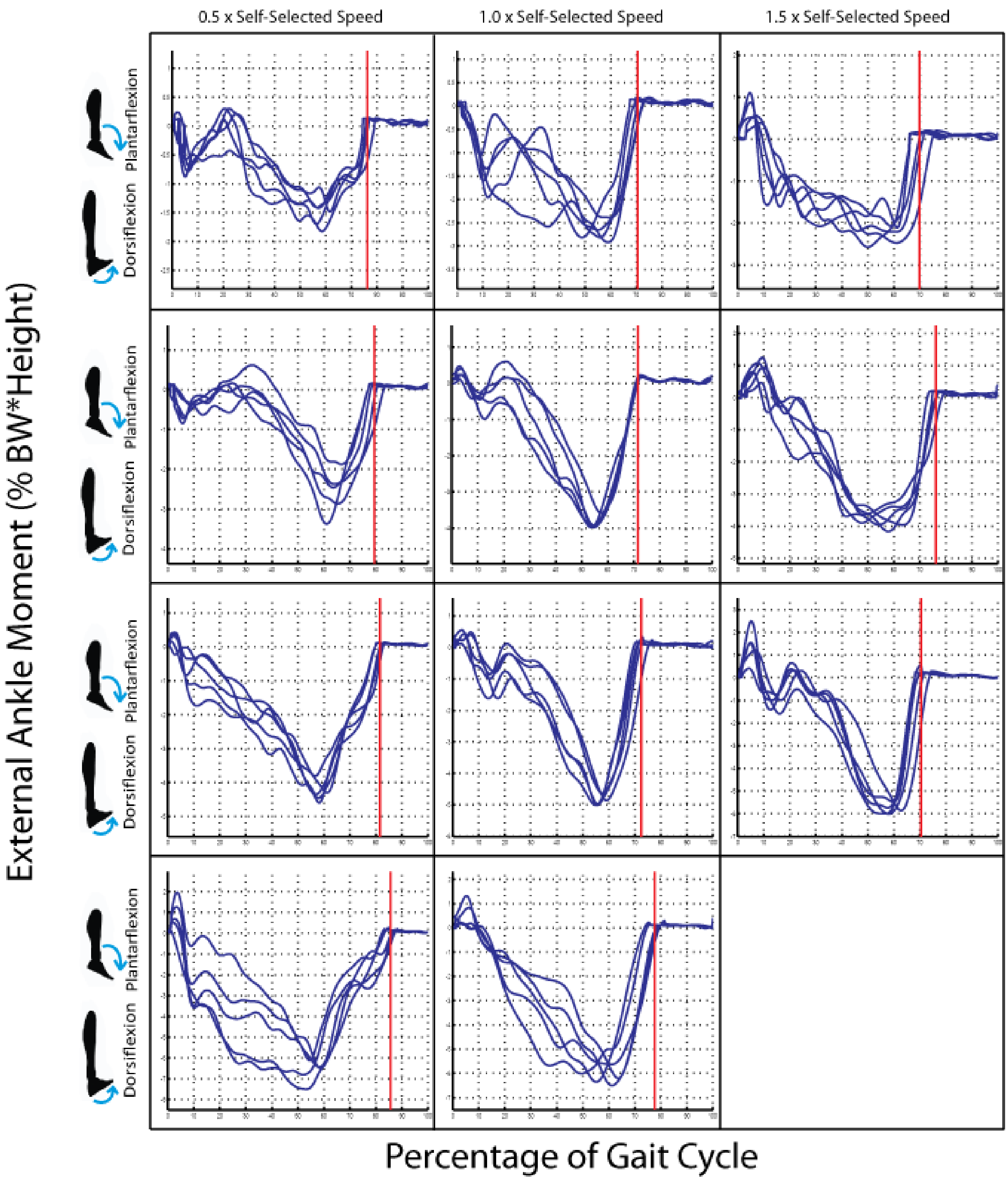

Figure 3.10: SCI patient's ankle moment for five gait cycles for 3 treadmill speeds and 4 levels of BWS. The red vertical line indicated toe-off.

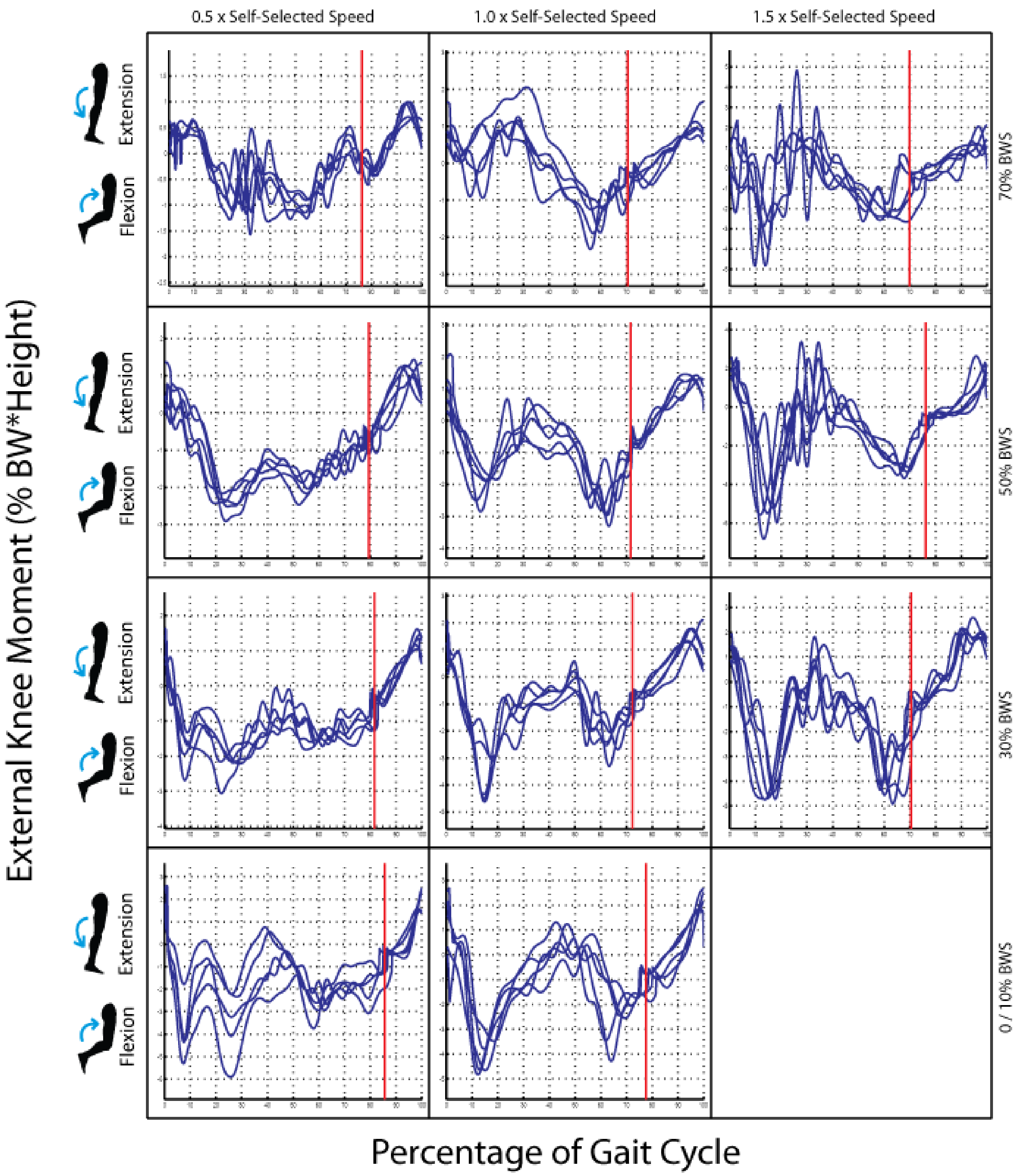

Figure 3.11: SCI patient's knee moment for five gait cycles for 3 treadmill speeds and 4 levels of BWS. The red vertical line indicated toe-off.

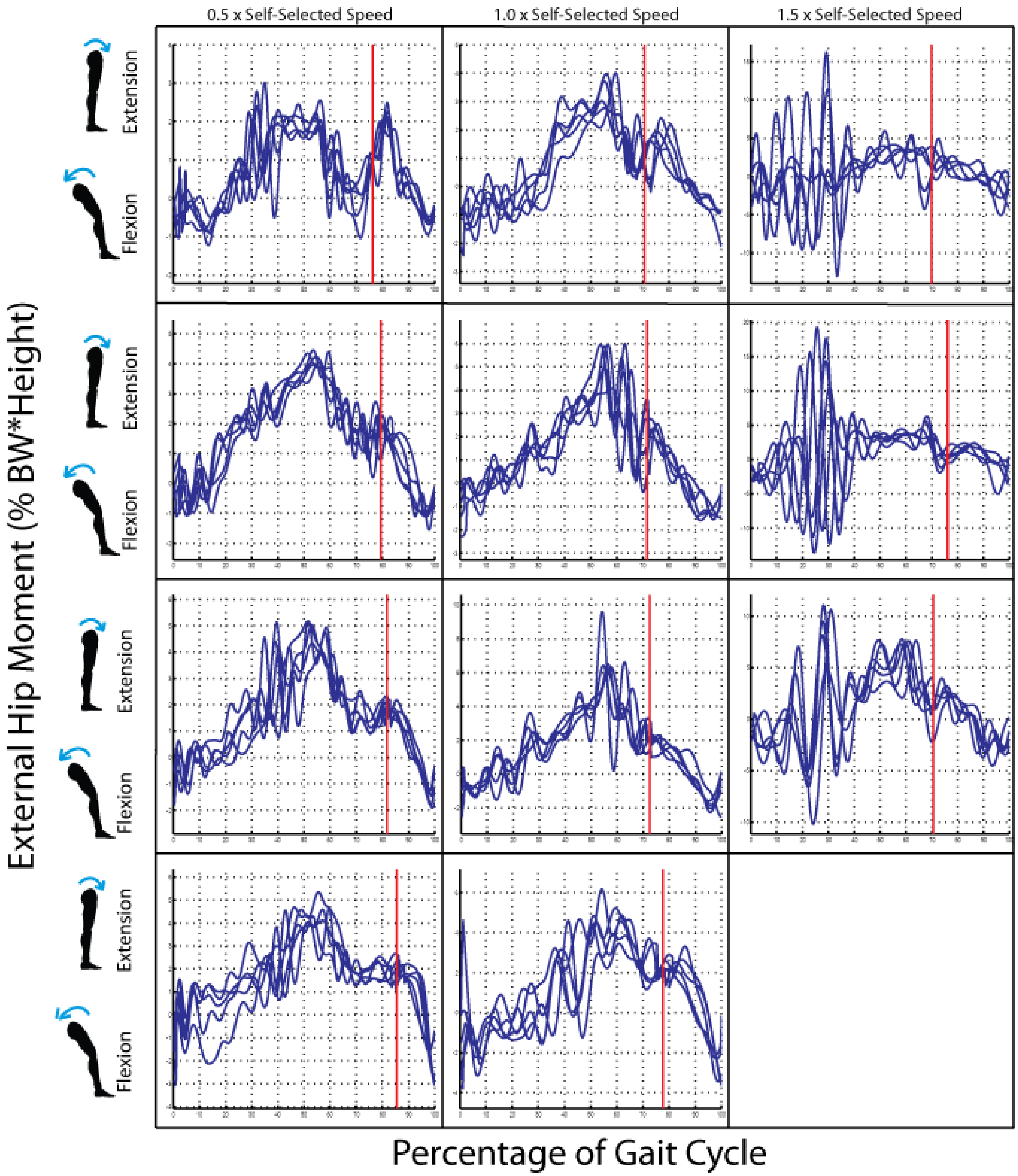

Figure 3.12: SCI patient's hip moment for five gait cycles for 3 treadmill speeds and 4 levels of BWS. The red vertical line indicated toe-off.

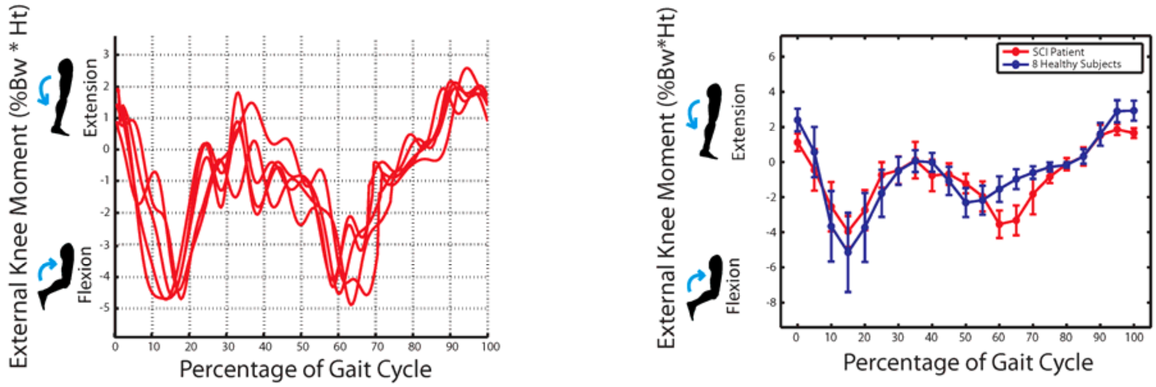

Figure 3.13: Knee moment for a) 5 gait cycles b) average of 5 gait cycles

3.2 Ankle-Foot Roll-Over Shape

An ankle-foot roll-over shape typically looks like an arc (Figure 3.14), and represents the rocker-like motion of the shank moving over the foot. Plots of the COP transformed into the shank-based coordinate system and the arc fit to the COP, representing the roll-over shape, are shown in Figure 3.15. For lower levels of BWS and faster speeds, an arc can be nicely fit to the data, and it looks like a typical roll-over shape. For higher levels of BWS and slower speeds, the transformed COP is erratic and there is no arc shape.

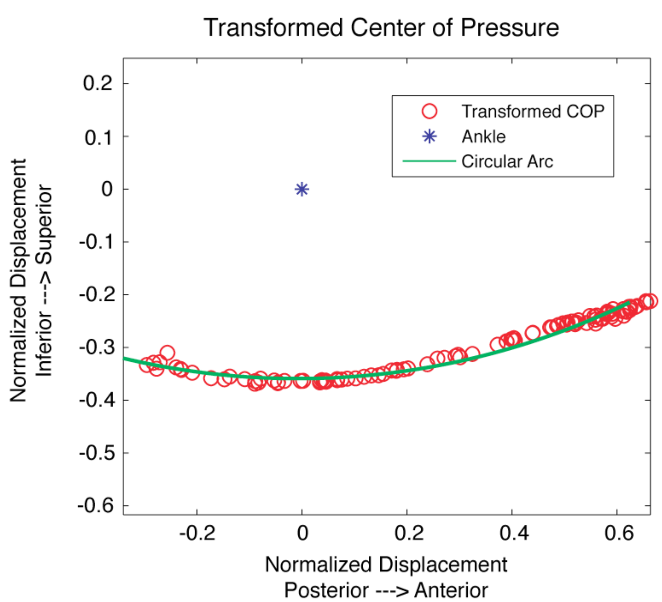

Figure 3.14: A typical ankle-foot roll-over shape from a healthy subject

While the radius and anterior shift of the ankle-foot roll-over shape were found for all conditions, as shown in Figure 3.16 and Figure 3.17, these values are difficult to analyze because the arc did not always clearly fit the transformed COP. For the conditions where a roll-over shape exists for the SCI patient, there is no clear trend in the data as speed and BWS are increased. When comparing the SCI patient to the healthy subjects, the radius and anterior shift are typically in a similar range of values.

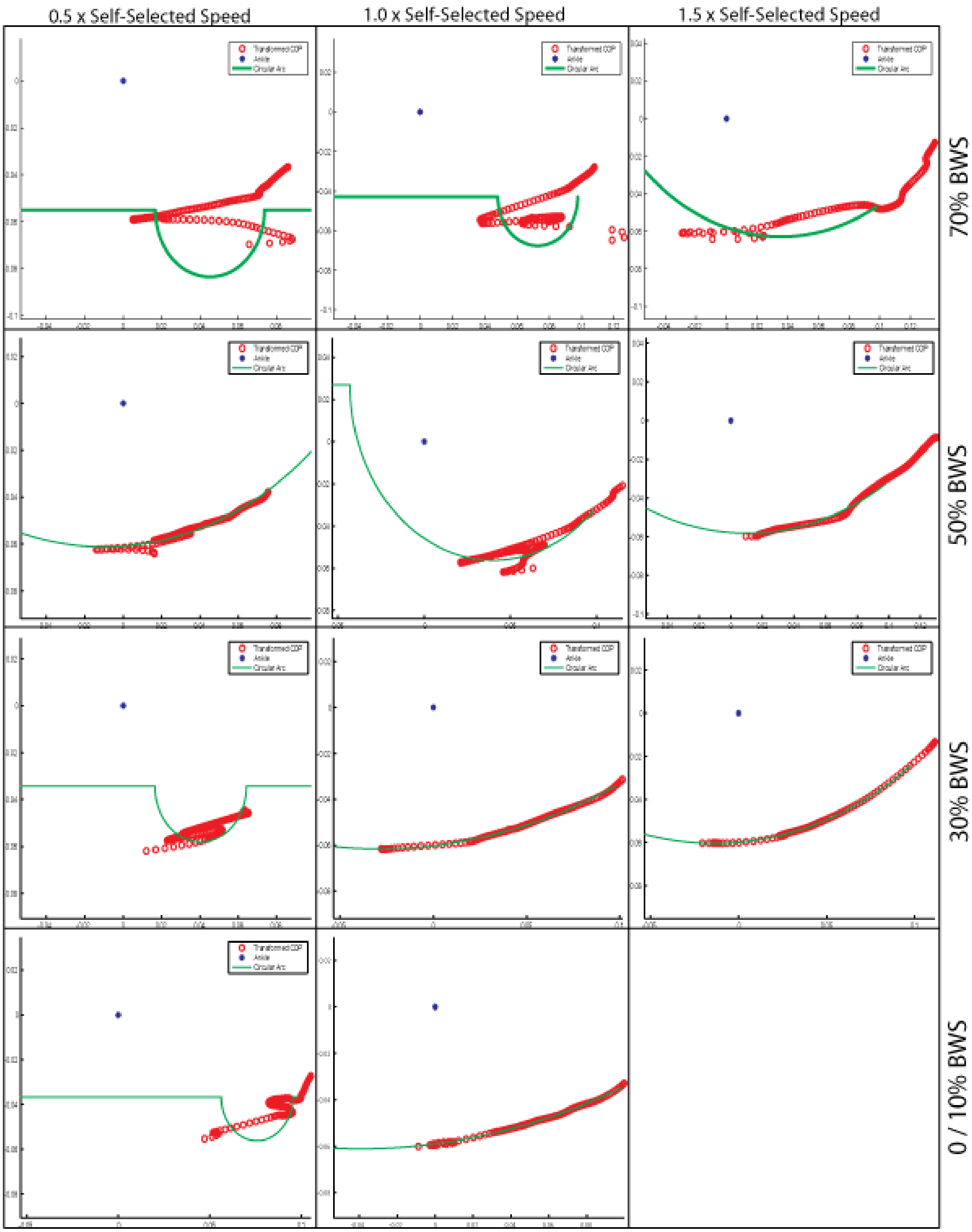

Figure 3.15: Ankle-foot roll-over shape for SCI patient

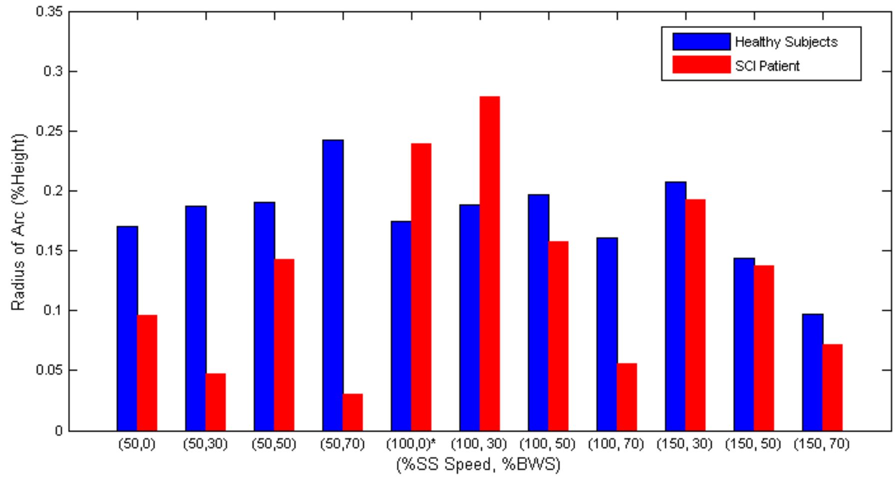

Figure 3.16: The radius of the roll-over shape arc for both healthy subjects and the SCI patient. *The patient had 10% BWS.

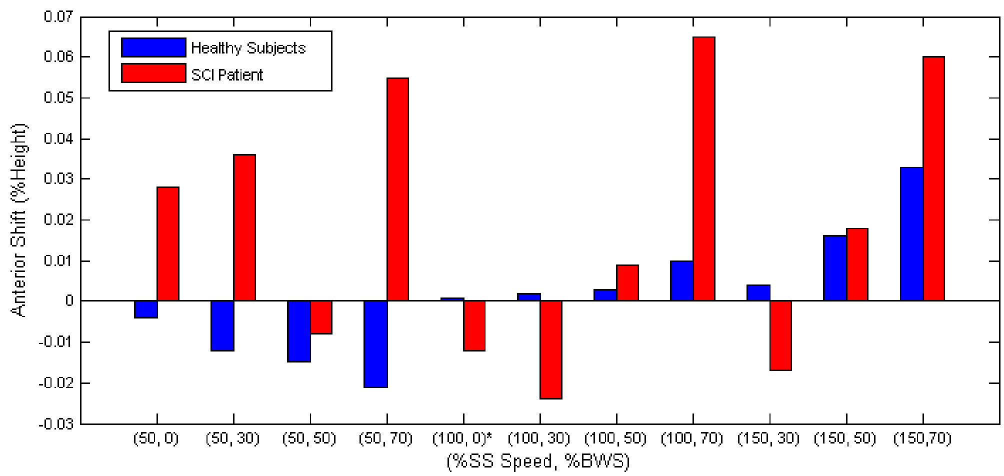

Figure 3.17: The anterior shift of the center of the roll-over shape arc for both healthy subjects and the SCI patient. *The patient had 10% BWS.

3.3 Foot Path

Comparing the path of the foot for one healthy subject and the SCI patient shows that the SCI patient's foot is more flat and closer to the ground than the healthy subject (Figure 3.18). The path of the foot for the SCI patient and 1 healthy subject for all conditions are shown in Figure 3.19. For a healthy subject, the foot moves in a repeatable, distinct path for all conditions.

The heel moves in a smooth motion, and the toe comes to a point on the most anterior part, which occurs during initial contact. For the SCI patient, the foot does not move in a repeatable path, especially at lower speeds and at higher BWS. The heel does not have the same smooth motion that is seen in healthy subjects, it has a sharper point on the most posterior. The path of the toe for the SCI patient is more rounded than the healthy subject.

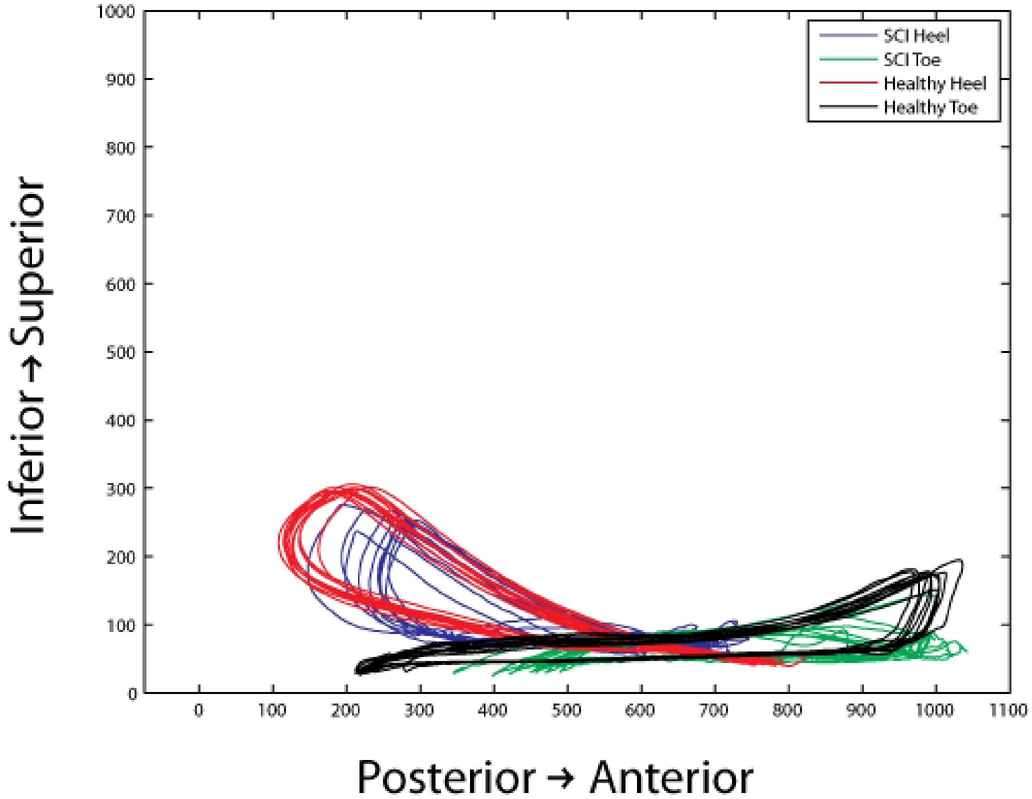

Figure 3.18: Foot path at 70% BWS, SS speed for SCI patient and 1 healthy subject

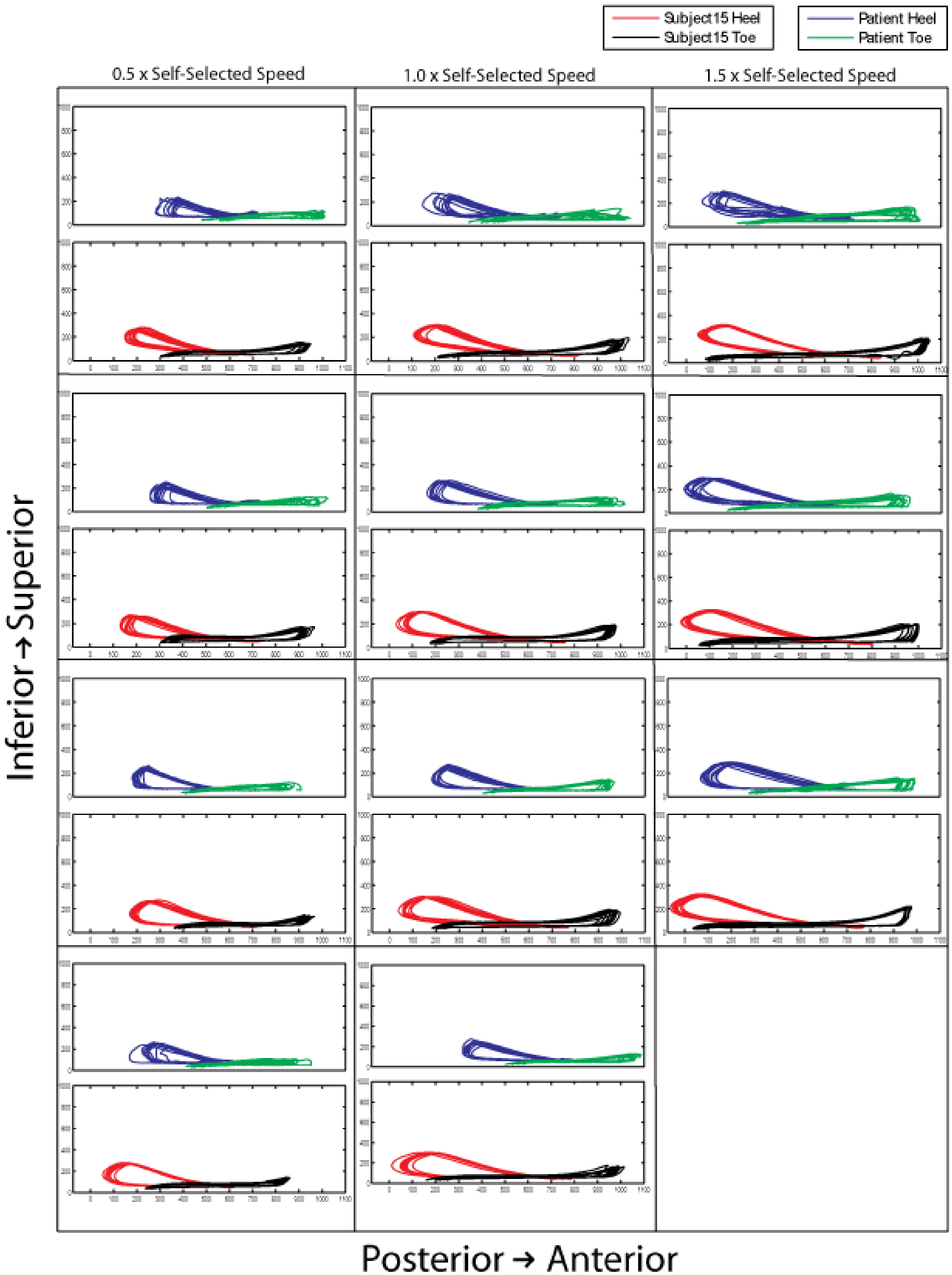

Figure 3.19: Foot path for SCI patient and 1 healthy subject

4. Discussion

It is unknown how individuals walk following BWSTT after an incomplete SCI. This research analyzed the gait patterns of one individual who had regained the ability to walk through BWSTT. The gait patterns were analyzed in the training environment with varying levels of BWS and treadmill speed and then compared to healthy subjects.

At high levels of body weight support and at the slower speed the patient makes initial contact with his foot flat on the ground. For many conditions the patient's foot remains flat on the ground, without much movement, throughout stance. The changes in ankle angle for these conditions during stance would be due to the movement of the shank. The increase in dorsiflexion at the ankle through most of the gait cycle could be caused by the greater knee flexion angle, which would move the shank closer to the foot. The patient making initial ground contact with a flat foot, as opposed to with his heel, could indicate the patient is experiencing toe drag through the swing phase, which is a problem for individuals with a SCI.

The path of the foot shows the lack of control the patient has of his foot. The foot path for the patient is not as constant and controlled as it is for the healthy subject. The path especially breaks down at higher levels of BWS. The greater knee flexion angle at early stance could be to compensate for this lack of foot control. If the patient does not have enough control of his foot to clear the ground without toe drag, he could be increasing the knee flexion angle in order to clear the ground during swing.

The SCI patient lacked consistent periods of breaking and propulsion throughout the gait cycle. This could be caused by the patient's lack of plantarflexion during toe-off, which would make it difficult to propel the leg forward through swing. Without this propulsion, the patient might not have sufficient time to fully swing his leg through, which could explain some of the differences from healthy subjects during initial contact with the ground.

A single peak in the vertical GRF, as was seen for the SCI patient, is also seen during chimpanzee gait (Crompton et al., 1998). Another characteristic of chimpanzee gait is greater knee and hip flexion. The SCI patient also walked with greater hip flexion, but hip angle was not included in this study. This similarities between the gait of a SCI patient and a chimpanzee show that a person who relearns to walk after a SCI could possibly be relearning a more primitive gait.

The high variability between gait cycles in joint moments and the average joint moments being similar to healthy subjects suggest this could be a feedback problem. The CPG uses cutaneous afferents in the foot and Golgi tendon afferents in the leg muscles to sense loading in the leg. The joint moments are most variable during midstance, when the leg is supporting weight, suggesting the feedback problem could be from these two afferent sources that sense load. Patients with SCIs have problems with sensation in the foot, which is used as feedback in the CPG. The variability increases the further the joint is from the ground, which would also be further from the cutaneous afferents in the foot. Individuals with SCI have spasticity, the rapid firing of muscles, and this could also be contributing to the high variability of joint moments.

The ankle-foot roll-over shape shows the variability in the COP, especially at higher BWS. This variability is not caused by the patient moving his foot, since the foot is on the ground throughout stance, but it could be caused by the patient shifting his weight back and forth while in the harness. SCI patients lack control of the trunk, and this instability could cause this shifting back and forth. While an arc can mathematically be fit to each gait cycle for the ankle-foot roll-over shape, the majority of the arcs do not represent the actual shape of the transformed

COP. The lack of a roll-over shape could show that the patient is not walking in the same way as the rocker-based inverted pendulum theory of walking, but possibly adapting another strategy.

Two training zones that are used often during therapy are high BWS and fast speed, or low BWS and slow speed. These parameters are chosen by therapists using kinematics and what looks like a normal gait. As seen in our results, at these conditions the patient's kinematics are similar to healthy subjects, while the joint moments are highly variably and a roll-over shape does not exist for the majority of these conditions. This supports research that shows the training parameters that are set based on kinematics do not produce accurate kinetics.

5. Conclusions

BWSTT is an effective therapy that help individuals with a SCI regain the ability to walk after injury, but improvements can still be made to this therapy, due to the resulting gait abnormalities and varying levels of results between patients. Currently there are no set standards for training parameters such as treadmill speed and amount of BWS, and these parameters are subjectively set by therapists. Since these parameters have been shown to affect the forces and motions in healthy subjects, and it is very important in BWSTT to replicate the forces and motions during normal gait, it is important to determine how these factors affect an individual with a SCI.

5.1 Contributions

This research project analyzed the gait patterns of an individual who had regained the ability to walk with BWSTT following a SCI. We found that the SCI patient had greater knee flexion than healthy subjects during initial contact for all conditions and the SCI patient made initial contact in plantarflexion at high levels of BWS. The SCI patient did not have periods of breaking and propulsion in the AP GRF, as are typically seen in healthy subjects. The joint moments for the SCI patient are variable between gait cycles, but the average for multiple gait cycles is similar to healthy subjects. The SCI patient also did not have an ankle-foot roll-over shape for most conditions.

These contributions provide information for how a patient walks following BWSTT, which was unknown before this research project. These results will help determine areas of focus for larger studies and will help with the overall goal of improving this therapy.

5.2 Additional Applications

Another application of this research could be to determine individual muscle properties during the gait cycle. OpenSim can be used to run a forward dynamic simulation to estimate individual muscle forces, lengths, and velocities. This research would give a good estimate for when muscles are lengthening and contracting, and if the timing for muscles is different in SCI than in healthy subjects.

5.3 Future Work

Since this study only studied one patient, it could be important to investigate the gait patterns of more individuals with a SCI. Everyone might respond to training in different ways, but similarities could exist between multiple patients. Some of the changes in gait patterns could be attributed to the way patients are trained, but this cannot be determined from one patient.

The cause of the high variability in joint moments deserves future investigation. Since it could be a feedback issue in the CPG, research could be done to determine the effects on altering the different afferent feedback sources in healthy subjects. Also, different populations with spasticity could be studied in order to determine if spasticity is contributing to this variability in joint moments.

5.4 Summary

The purpose of this pilot study was to analyze the gait patterns following BWSTT and determine any difference from healthy individuals. We tested one subject at varying levels of treadmill speed and BWS and found this joint kinematics, joint kinetics, foot path, and ankle-foot roll-over shape. One of the main differences between the two groups was the lack of foot and ankle control in the SCI patient. Also, the joint moments were variable between gait cycles for the SCI patient.

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